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Section 1 of this progress report reviews the background and ongoing research into creativity in engineering design. Both expert designers and inexperienced subjects are being processed; after tests of learning style, both groups perform an individual design task (constructing an electronic analogue simulator for demonstrating aspects of reaction kinetics), and a further team task. Section 2 exemplifies one method for comparing data about design behaviour which is obtained during analytic sessions, using

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Progress Report No 6

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THE INFLUENCE OF LEARNING STRATEGY
AND PERFORMANCE STRATEGY UPON
ENGINEERING DESIGN

1 January 1977 - 31 March 1977

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Contractor's signature ....

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Index

1. INTRODUCTION

1.1. Background

Previous Progress Reports, 1, 2, 3, 4, 5, Scientific Note No 1 and Scientific Note No 2, have covered research to date, on a study of engineering design in relation to individual learning style. Learning style is determined by an initial computer administered test, which is described in Scientific Note 1, and classifies individuals in terms of propensity to engage in "operation learning", in "comprehension learning" and "versatility learning" (the main test variables). Experimental subjects are divided into two groups, A and B, experienced designers and student designers, respectively. A sub category, selected from subjects showing low versatility in the initial stylistic pretest, undergo specific versatility training.

The performance of all subjects is examined over two design tasks; one individual (the design of a reaction kinetics simulator for tutorial use) and the other a team task intended to sample communication between designers (skilled or not). In the team task more complex simulation designs are attempted and different criterial constraints are in force. The criteria to be satisfied, so far as possible, by any design are as follows : (A) Reliability, (B) Transparency, (C) Weight/Cost/Size, and (D) Environmental Sensitivity, but their relative importance in the 1st (or individual) design task and the 2nd (or team) task, are quite different. Part of the 2nd (team) task is to assemble the simulator models manufactured during the 1st (individual) task, in order to simulate complex chemical reactions.

Apart from protocols, behaviour recordings and notes, made during the (5 to 11) design periods, designers are required, at the end of each period, to take part in an analytic session during which they interact with a computer regulated interface (THOUGHTSTICKER) and provide an explanation or justification of the design they have produced, up to this point, in a standard, non verbal, format. Detailed records are presented in Scientific Note No 2 (which accompanies Progress Report No 5) and it is notable that this recording method :

20. <u>Abstract</u> (continued)

a man machine interface, after each design session (between 5 and 11) for the 1st task); this data, which augments notes and a physical realization of the design, is an on-line, non-verbally elicited, explanation of how and why a subject produces his design. Most subjects also explain how their design relates to operation in an application domain. Section 3 of the report exemplifies the type of personal and interpersonal design evaluation, using 4 criterion variables, which all subjects are required to furnish at the end of the first (individual) design task. Section 4 introduces a generalisation arising from the ongoing research. Descriptions of each design and its standard-format explanation (which includes reference to the application domain, in this case, physical chemistry) are elicited from, and exchanged between, subjects in the present study. But the technique can be extended to members of an evaluation team presented with alternative designs (satisfying the same brief) and the standard-form explanations which relate them to an application domain. It is believed that the extended technique could provide a potentially useful method for evaluating alternative designs of any kind. Section 5 refers to procedural matters, notably, a revised and simplified first-task design brief (shown in Appendix 1), a subject questionnaire (shown in Appendix 2) and means employed for training subjects to adopt a versatile point of view.
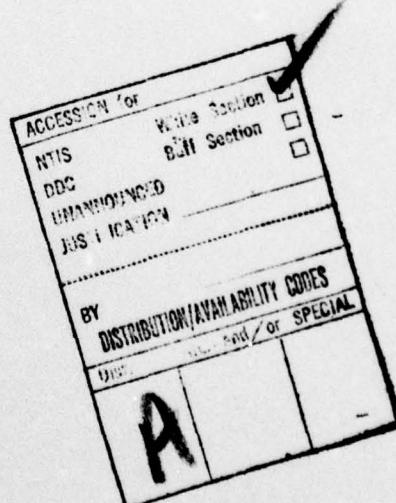
(a) Extracts an explanation of the "how" and "why" of a partial
or complete design in a standard and quantifiable form.

(b) Shows the different perspectives or points of view considered
significant and adopted by each designer.

(c) Relates his mathematical reasoning, his concrete construction
(an electronic circuit which is part, or all, of a design) and his
reasoning about the domain of application; namely, demonstrating
the principles of chemical reaction kinetics and chemical
equilibrium.

1.2. Progress in the Reporting Period

Experiments are in progress. The time occupied by the 1st
design task (completed when a working simulator is constructed
using the modular assembly equipment of Fig 1) is longer than
expected, even though the design brief was modified to cut down
time that seemed to be spent unprofitably (Progress Reports 3, 4,
and 5). However, the information obtained by the analytic method
using THOUGHTSTICKER is more detailed than we anticipated and
produces especially valuable individualised data about the
designers concept of the application domain. Some subjects do
and others do not keep design application in mind, as a matter
of course, thoughout their work. There are also interesting
individual differences in the extent to which designers mathematicise
their task in contrast to building up concrete representations, using
the module assembly equipment of Fig 1, as they go along: ultimately,
in all cases, a concrete and working circuit is required which
satisfies the design brief and, so far as possible, meets the
criterial constraints of reliability, transparency, weight/cost/
size and environmental sensitivity. 8 (non pilot) subjects
have completed the 1st design task.

Progress in the 2nd (team) design task is more difficult to
estimate since team sessions are hard to organise. Amongst other

reasons, because of the geographical distribution of subjects, Fig 2 of Progress Report 5). Only one team has run through the open ended 2nd design task and one other team is in progress, though arrangements have been made to accommodate all subjects who have completed the 1st design task or who are in the process of doing so at the moment.

The substantive contents of this report are as follows : Section 2 contains a discussion of the quantification of data obtained by Q Analysis (Appendix, Progress Report 5); sample analyses for the material in Scientific Note 2 are included. Section 3 is an account,with examples,of the design evaluation carried out on completion of the 1st design task. Section 4 sums up the question of evaluation, in general, since a natural but novel evaluation technique has been discovered. Section 5 deals with procedural matters including the simplified design brief (Appendix 1) and the subject questionnaire (Appendix 2) which is administered over and above the computer administered stylistic test and other tests noted in Progress Report 4.

2. Numerical Analysis of Data Using the Q Analytic Method

The Appendix of Progress Report 5 gave a terse summary of the Q Analytic technique, due to Atkin (1974) and showed, incidentally, that the complexes obtained are (in the mathematical sense) a category, under transitive closure, as an operation. Q Analyses are carried out on the standard graphical type explanatory representations (as in Scientific Note No 2) obtained during analytic sessions and permit comparison of the complexity and connectivity of different designs.

The analysis is performed by an auxiliary LISP program to which the data in question are input.

Various kinds of analysis are possible and potentially useful; for example, it is possible to examine the session-by-session progress of one subject and possibly to obtain between-subject comparisons on a session-by-session basis.

One kind of analysis which is peculiarly important is to compare the explanations of final designs. Thus, at the end of the 1st Design Task, each designer has produced a simulator model which satisfies the design brief and that actually works. Since these simulations do the same thing (perhaps in very different ways) there is a standard condition. The final designs of different 1st task subjects may thus be compared; so may the very different explanations offered, at this stage, by the designers (notice, these explanations all include the design itself, but also include reference to the application domain). The final design meshes (explanations) for subjects 5 and 6 (see Scientific Note 2) are reproduced in figures 2a-2f. Q Analyses for these meshes are shown in figure 3.

So much psychologically interpretable, but detailed, numerical data is available to augment the measures noted in Progress Report 4 that its intelligible representation requires careful thought; several possibilities are being considered at the moment; choice between them must await further data, but the

Q Analysis program is efficient and no particular difficulty
is anticipated in selecting a suitable representation scheme
of which the individual explanation of final designs (Fig 2a-2f)
is one component only.

3. Description Schemes

As discussed in Scientific Note 2, the designer subject is required to explain his design in terms of a standard entailment mesh which he can view from any perspective by pruning it automatically. Further, at least for his final design, he is required to describe a pruned mesh by citing descriptions (many valued predicates with one reserved value "*" for irrelevant or inapplicable) and giving their values on the nodes of the entailment mesh that represent topics or components or functions. The method is a systematic extension of the repertory grid technique used for eliciting Kelly's "Personal Constructs" (Bannister and Mair 1968 and Bannister Ed,1970).

Apart from the chosen descriptors the criterial conditions Reliability, Transparency, Weight/Cost/Size and the environmental sensitivity of the design are added as mandatory descriptors.

The final design mesh (the students explanation of a final design) provides a "standard condition". All such meshes (explanations) include representation of (and may be pruned under a node representing) a simulator model which does the same thing as any other, though many designs are possible.

The mandatory descriptors have other than "*" values over nodes (components or functions) of the embedded explanation of this simulator design (even though they may, or may not, have relevant values on other nodes.)

(a) The designer necessarily assigns relevant values of Reliability, Transparency etc to his own mesh.

(b) This furnishes a detailed (as compared to a gross) self evaluation of his design.

(c) Since the nodes in this part of the mesh stand for mutually recognisable components or functions another designer can assign values of the same criterial descriptors (which he may interpret differently) to his colleagues design.

(d) The descriptors are comparable by standard methods of rank correlation provided that the assessors in question are agreed that certain components or functions in each design explanation are equivalent (the overall function _must_ be; many parts, such as display devices, almost certainly _are_; recall, the assessors have a concrete piece of equipment in front of them).

Fig 4 and Fig 5 show such an assessment and value assignment for the final design meshes of Scientific Note 2 and Fig 6 shows an analysis and comparison of this data.

4. Some Principles of General Design Evaluation

Design "Evaluation" has always been a contentious topic. People are uneasy (rightly so) of rank ordering "a design" on one dimension (for example, of overall performance) or even assigning it a value over many dimensions (such as "Reliability", such as "Transparency" ....) however aptly these are chosen and however precisely they are specified.

Frequently, choices based upon evaluation are made as a result of agreement amongst a group or committee of scrutineers made up from users (perhaps with different views of the domain of application), equipment experts and cost benefit experts. Ideally, it should be possible to provide a data base, initially structured by the designers of different designs but updated by the agreed opinions of the scrutineers, which can be interrogated (and progressively updated) by the scrutineers with the object of obtaining an increasingly coherent and representative selection.

The method of eliciting and assigning values to the descriptors of a design is a step in this direction. In Section 3 emphasis was placed, for experimental purposes, upon the mandatory descriptors (reliability, transparency, weight/cost/size, environmental sensitivity) which have relevant values on the design itself, but, on general theoretical grounds (Pask 1975, 1976), the meaning of "evaluation" is more closely bound up with the entire design explanation and those descriptor which also have relevant values on topics in the application domain.

Suppose that a class of designs (say, 5 or 6 of them) are explained in terms of an entailment mesh, the topics in which are covered by all of the descriptors. Let this description be the initial data base, indexed by the explanatory mesh, which is presented to the scrutineers, together with models and performance characteristics of the designs in question.

This is the initial data base available to the
scrutineers; it consists in several designers explanations of
their own designs, together with their possibly faulty or
incomplete ideas of how they will perform in the application
domain and the descriptions they have given.

There exists a partly mechanised (man/machine) system
for manipulating "exchange grids" (Thomas 1971); that is, for
updating personal descriptions of objects (in this case topics,
components/functions of a design) so that, for example, Subject
5's description of Subject 6's design can be traded against Subject
6's description of Subject 5's design. The method does not change
the objects (in this case the design explanations) but it may, as
a result of personal interchange, alter the values assigned to
descriptors and, quite commonly also, the set of descriptor names.
Any agreement leads to a convergent description. As the method is
a heuristic, convergence cannot be guaranteed but, in practice,
often takes place, ie. some commonly agreed description is sharpened
up and stabilised as a result of an interactive process.

Consider next the situation in which the designers
(Subject 5 and Subject 6 in this case) are replaced by the
scrutineers (Subject 5 and Subject 6 have had their say in the
matter by providing an initial descriptive data base for the
scrutineers to interrogate). The scrutineers, at this stage,
interact in the "exchange grid" mode. They cannot change the
design explanations, but they can engage in a process, hopefully
convergent, in which they sharpen the values of existing
descriptors and possibly select different descriptors (elicited
from the scrutineers rather than the designers). Insofar as
the resulting description scheme converges and is agreed, it
provides a basis for rationally selecting between alternative
designs and possibly for recommending modifications to one or
more of them.

According to this view the word Evaluation stands for
a process (namely the iterated interaction between the scrutineers,

5. Procedural Matters

(a)   Attempts to use take away construction kits (suggested in Progress Report 5) have not been successful and practical work is being carried out at the laboratory.

(b)   The use of THOUGHTSTICKER, during analytic sessions, in its active mode <u>does</u> appear to be a satisfactory method of versatility training and is acceptable to subjects.

(c)   Appendix 1 is a specimen copy of the revised and simplified design brief (supporting materials are given to the subjects but are not included in this specimen).

(d)   Appendix 2 is a copy of a questionnaire, administered to all subjects before the experiment.
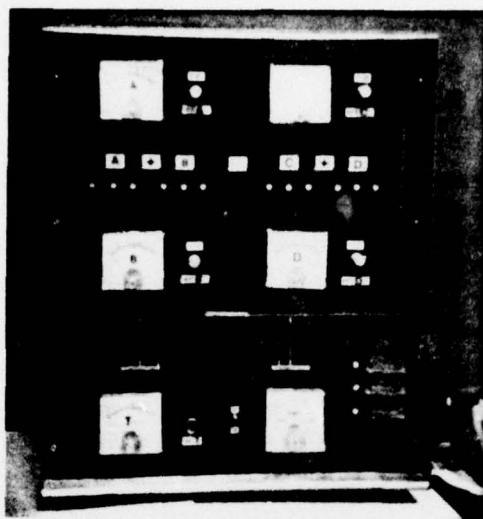
(a) Prototype Display Panel
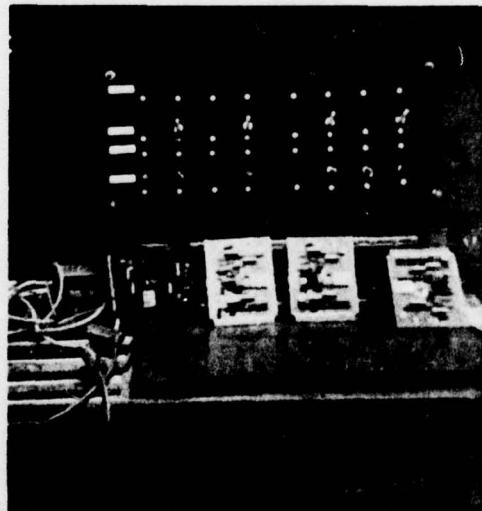
(b) Circuit modules, bread board, prototype control
and monitoring panel

Fig 1. Simulator Prototyping Equipment
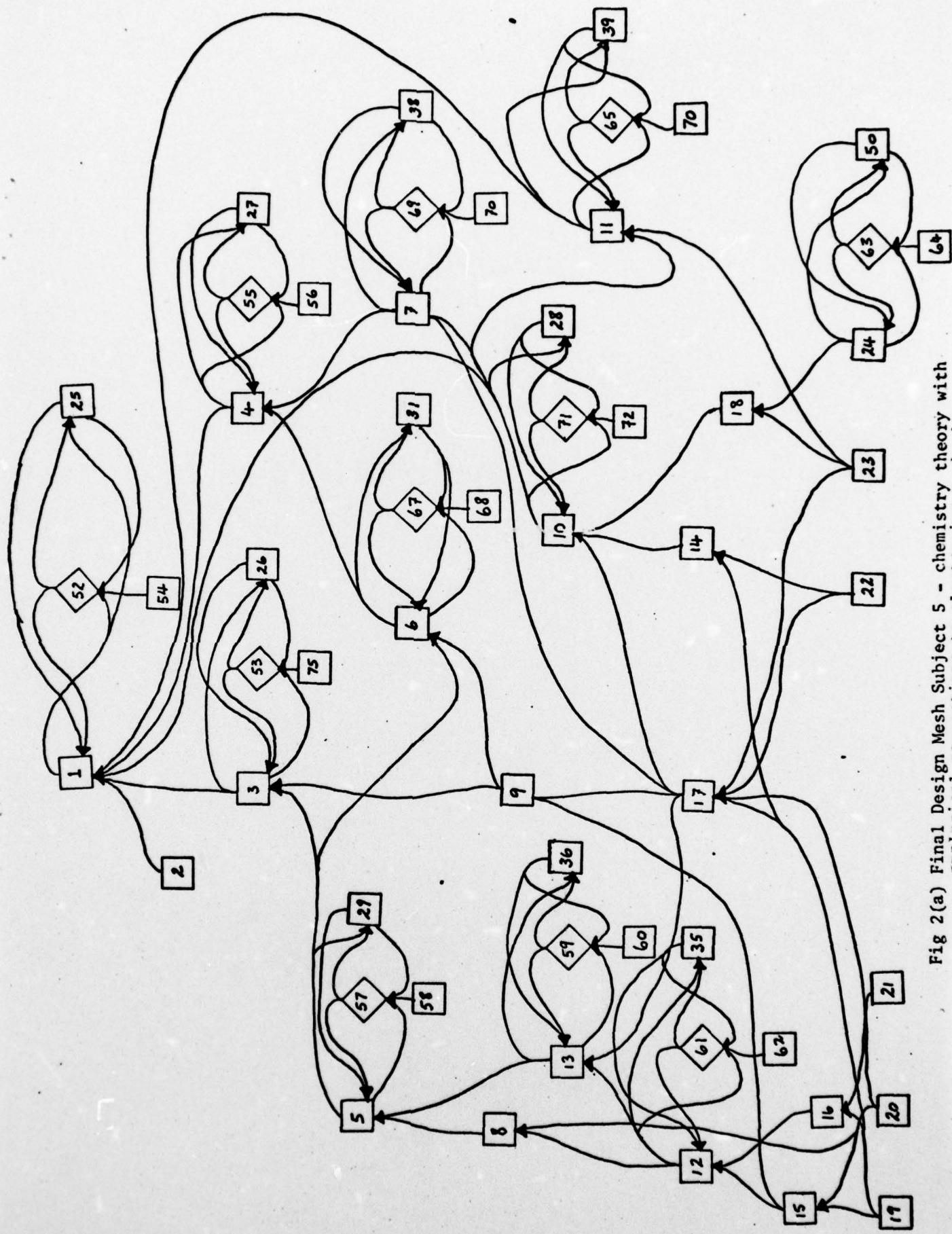
Fig 2(a) Final Design Mesh Subject 5 - chemistry theory with analogical connections to electronics mesh shown
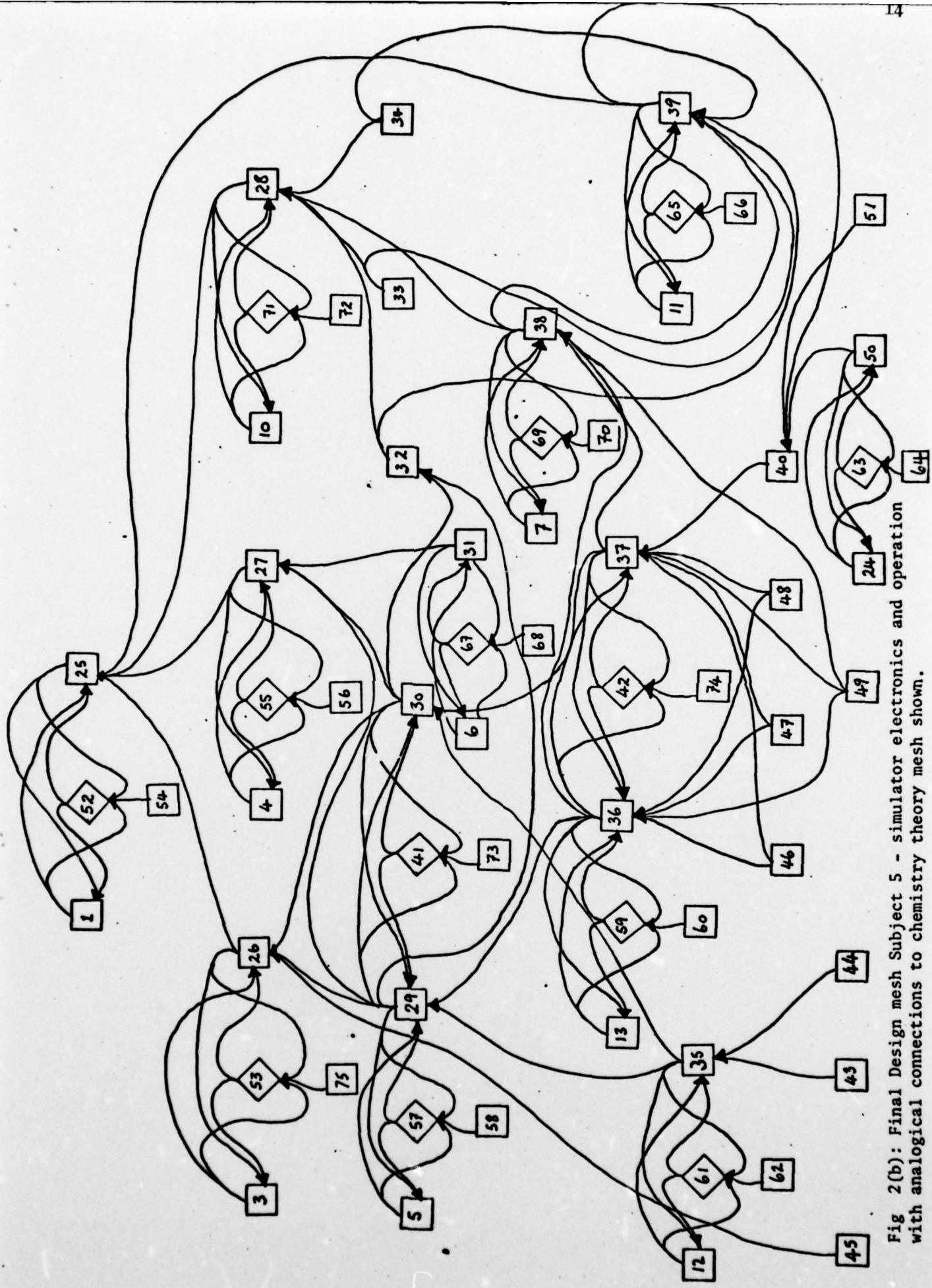
Fig 2(b): Final Design mesh Subject 5 - simulator electronics and operation with analogical connections to chemistry theory mesh shown.

1. Theory of behaviour of elementary reaction system
2. Solution of differential equations
3. Net rate differential equations
4. Equilibrium constant as a function of temperature and ΔH
5. Differential rate equation with K (rate constant) as a function of temperature.
6. Equilibrium constant derived by equating forward and reverse rates
7. Relationship between ΔH and E_F^* and E_R^*
8. Differential rate equation for constant temperature
9. Reversible reactions.
10. ΔH as a result of molecular bond breaking and formation
11. Reaction temperature as an arbitrary function of ΔH and extent of reaction
12. Definition of rate for each substance in stoichiometric equation
13. Arrhenius function $K = Ae^{\frac{-E^*}{RT}}$
14. Molecules with structure and bonding
15. Stoichiometric equation
16. Definition of concentration
17. Collision model: activation energy, kinetic energy temperature.
18. Constant temperature reaction condition
19. Simple concept of molecules (hard spheres)
20. Simple collision model of reaction
21. Mass/amount of substance
22. Molecular kinetic energy
23. Temperature
24. Thermostat

25. Electronic analog simulation of behaviour of elementary reacting system
26. Solution of differential equations using analog integration. Display variables as a function of time.
27. Equilibrium constant as a function of temperature and ΔH.
28. Approximate computation and display of heat in/out (thermostat on)
29. Forward rate expression computation module (K_R as a function of temperature)
30. Reverse rate expression computation module (K_F as a function of temperature)
31. Equilibrium conditions in electronic feedback systems/oscillators
32. Net rate (λ net) as voltage variable
33. Integrator with arbitrary scaling
34. Op. amp. comparator
35. Scaling rate variables (division by stoichiometric) coefficients
36. Arrhenius function computation (K_F)
37. Arrhenius function computation (K_R)
38. Computation of ΔH using subtractor
39. Computation and display of reaction temperature (thermostat off) using comparator and integrator
40. Temperature as voltage variable
43. Division by a constant using potential divider
44. Stoichiometric coefficients as user controls
45. Analog integration
46. Analog summation/subtraction
47. Analog exponential function using antilog amplification
48. Analog multiply/divide using transconductance multiplier
49. A and E^* as user controls
50. Thermostat on/off control
51. User temperature control

Analogical Topics	Correspondence Between		With Restrictions and Distinction
41	29	30	73
42	36	37	74
52	1	25	54
53	3	26	75
55	4	27	56
57	5	29	58
59	13	36	60
61	12	35	62
63	24	50	64
65	11	66	39
67	6	31	68
69	7	38	70
71	10	28	72

Fig 2(c) Topic Names . Final Design Mesh, Subject S.

16
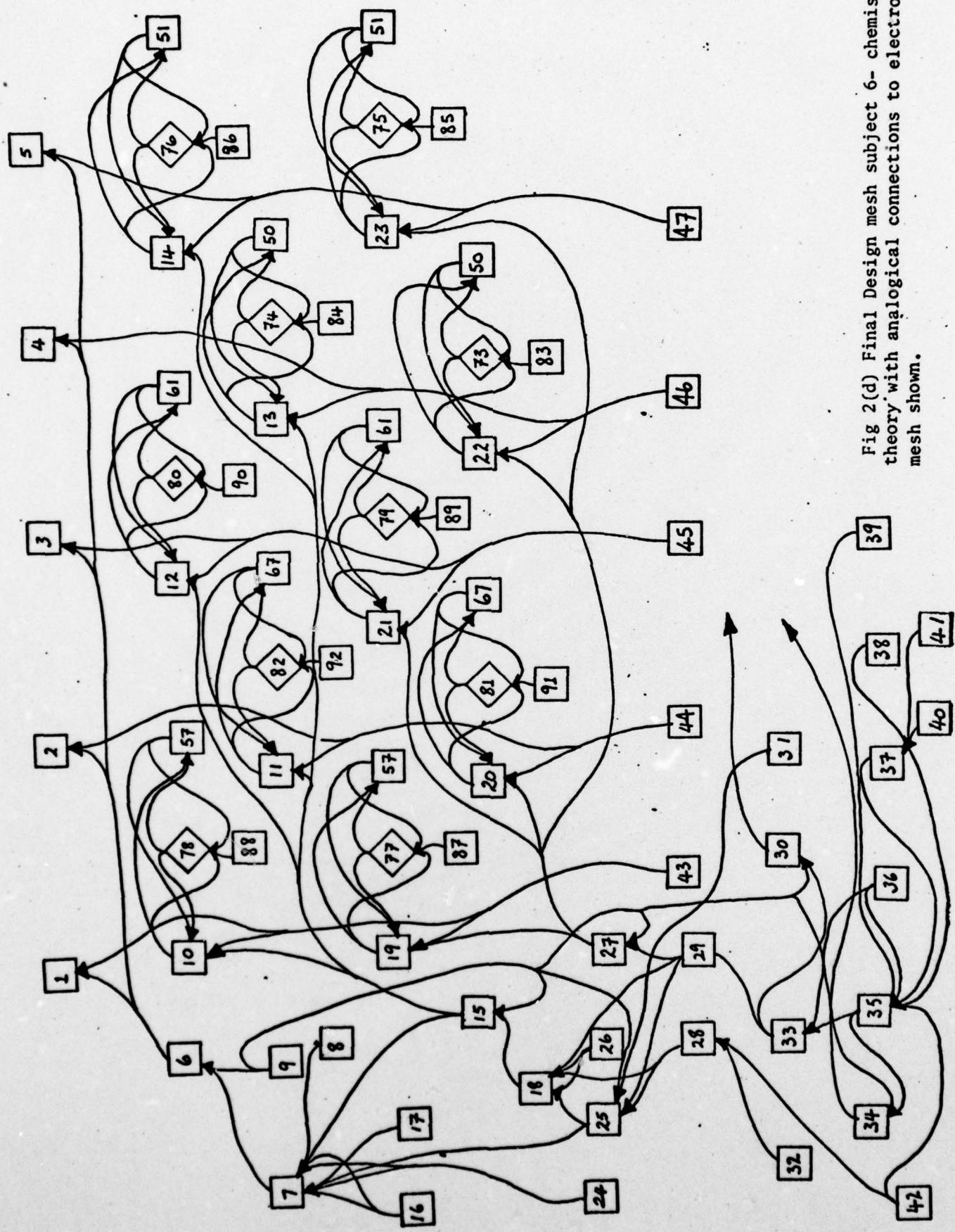
Fig 2(d) Final Design mesh subject 6– chemistry theory with analogical connections to electronics mesh shown.
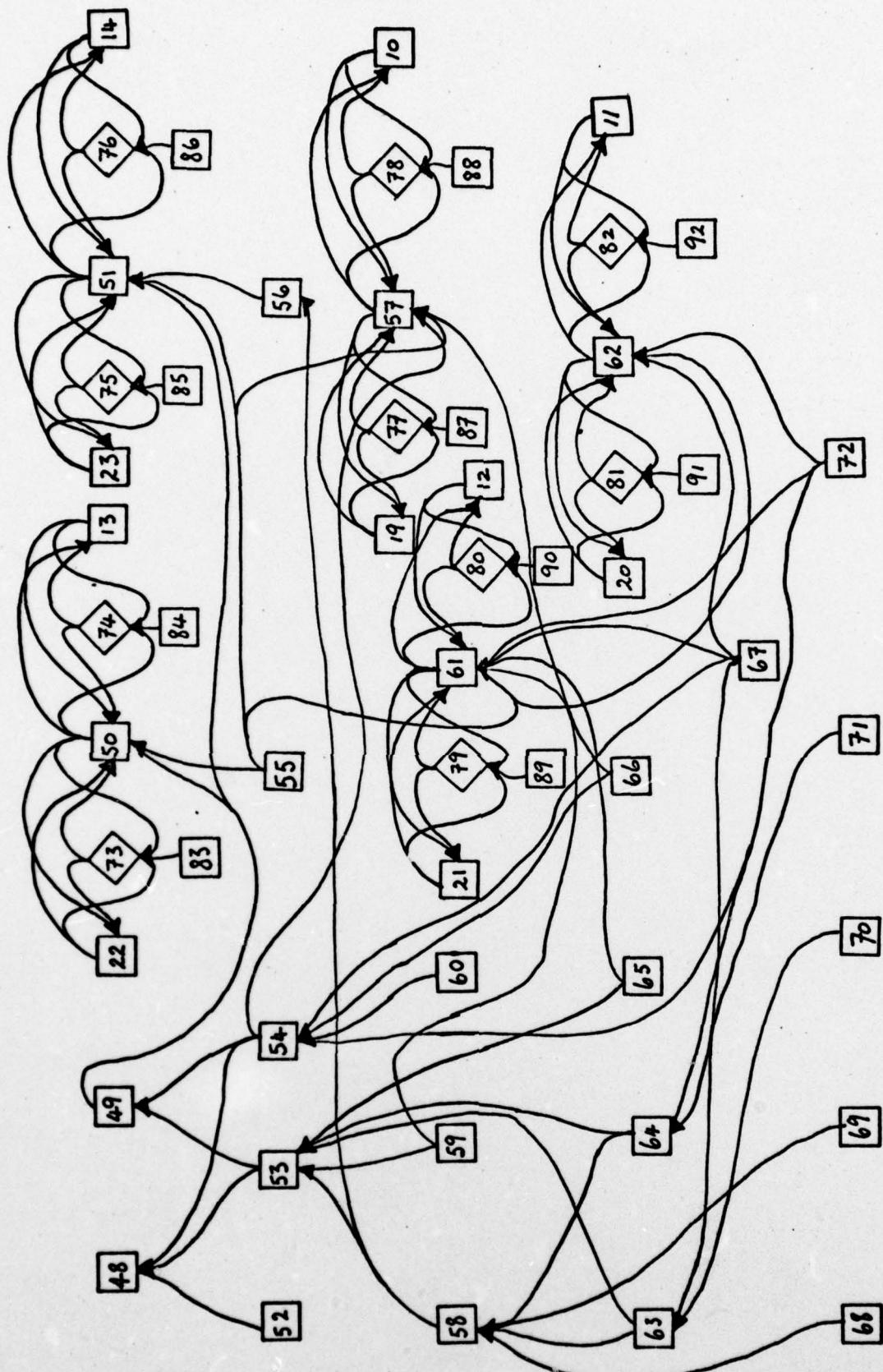
Fig 2(e): Final Design Mesh subject 6— simulator electronics and operation with analogical connections to chemistry theory mesh shown.

1. to 5. Behaviours type 1 (constant concentration)
   Type 2 (constant temperature) Type 3 (reversible and
   irreversible) type 4 (temperature computed as variable)
   Type 5 (rates, equilibrium constant as function of temperature)
   For "Resonance Model" RM.
6. All R_M Behaviours
7. Resonance Model RM
8. Distribution and averaging in any partitioned closed system
9. Temporal sequence
10. to 14. Behaviours Type 1 to Type 5 for Multiple Path (or complex)
    Model MPM
15. All MPM behaviours
16. Vibrational Energy
17. Thermodynamic Principles
18. Multiple Path (or complex) model MPM
19. to 23. Type 1 to Type 5 behaviours of Idealised simple path
    model ISP
24. Transfer of energy over finite interval (resonance)
25. Activated complex hypothesis as special case of the MPM
26. Rarity of simple path reactions
27. All behaviours of idealised simple path reaction model
28. Activation level
29. Idealised simple path reaction. Model with potential energy of
    configuration included.
30. Behaviours of various collision orders (trivial)
31. Restriction to activation complex form of multiple path reaction
32. Discrete events
33. Collisions of integral order model
34. Behaviours of simple collision model (trivial)
35. Simple Collision model
36. Multiplication of probabilities rule.
37. Particles
38. Haphazard (probabilistic) motion
39. Closed system
40. Unitary or simple particles
41. Complex particles
42. Probability as function of mean kinetic energy
43. Empirical conditions for constant concentration of reactant
44. Empirical conditions for constant temperature
45. Reversible and irreversible processes
46. Determination of variable temperature (function of reaction)
47. Determination of equilibrium constant and rates
48. Complex reaction obtained by serial or parallel combination
    of simple reactions and their energetic exchanges in reaction
    vessel.
49. Simple reaction
50. Energetic behaviours
51. Rate and equilibrium constant (k) behaviours (computed value temperature)
52. Cartesian product
53. Energetic simulation
54. Reaction simulation (energy is discounted)
55. Temperal sequence
56. Computer temperature
57. $= 24*$
58. Temperature (T) = 8
59. Constant temperature Δ H displayed
60. Manual switching of orders of reaction
61. Behaviour of k and rates at manually varied temperature
62. Behaviour of rates and of equilibrium constant at fixed $T = T^*$
63. ΔH_F
64. ΔH_R
65. Manually variable temperature
66. Concentration of reactants.
67. Simplification (formal condensation) of Mesh III (2) (Research Note 2) under
    'forward reaction' (node 6, Mesh III (2)) (Research Note 2)
68. Log A_F
69. Log A_R
70. E_F
71. E_R
72. Simplification (formal condensation) of Mesh III (2) (Research Note 2)
    under 'reverse reaction' (node 11, Mesh III (2)) (Research Note 2).

Analogical topics	Correspondence between		With restriction and distinction
73	22	50	83
74	50	13	84
75	23	51	85
76	51	14	86
77	19	57	87
78	57	10	88
79	21	61	89
80	61	12	90
81	20	62	91
82	62	11	92

Fig 2(f) Topic names, final design mesh, Subject 6.

Explanation of Figures 3(a) and 3(b)

Q analysis provides a measure of the complexity and connectivity of an entailment mesh.
Complexity is indexed by the number of topics utilized in deriving a particular topic. For example, in the mesh for Subject 6, nine topics are required to derive topic 61. These nine are said to be the kernel topics for topic 61.

The Q analysis program first lists the topic or topics with the largest kernel(s).
For subject 6, this is topic 61, with nine topics in its kernel.

The program then lists these topics with eight (or more) topics in their kernels. For subject 6, only topic 61 qualifies. The next list is of topics with seven (or more) topics in their kernels. For subject 6, four topics qualify: 61, 51, 57, 52

This process of listing by kernel size continues down to listing all topics with one (or more) topics in their kernels. For subject 6, there are 50 such topics.

Topics not appearing in this list are primitives: they have empty kernels and are the topics that the subject expects anyone studying his mesh to already understand.

Connectivity is indexed by considering the degree to which the kernels of two or more topics share members.

The Q analysis program, at each listing of topics whose kernel size is $\geq$ n (recall, for subject 6, n ranges from 9... 1), partitions off sublists of topics whose kernels share n or more members.
For subject 6, the first such sublist with more than one topic, occurs when n = 3.
Partition no. 14 contains two topics: 61 and 62, which means three topics are shared by the two kernels. When n = 2, there are several such partitions: partition no. 1, for example, contains 7 topics. When, as here, there are more than two topics in the partition, the requirement is that each topic must share n members with at least one other topic in the list.

Thus, the members of the partition have a particular degree (n) of connectivity, amongst themselves but it is not always the same n topics that form the connection.

The motivation for the analysis is to obtain indices that can be given a psychological interpretation when meshes are compared. The two analyses listed, show that subjects 5 and 6 have very similar degrees of complexity as indexed by numbers of topics with a particular kernel size. Marginally, subject 5 shows greater connectivity: for n = 5, n = 4, n = 3, he has five partitions containing more than one topic. Subject 6, as already mentioned, has one such partition when n = 3, and non when n is $>$3.

When n = 2, subject 5 has five such partitions involving 18 topics. Subject 6 has 7 such partitions involving 20 topics.

Fig 3a. Q Analysis Program Output for final design mesh, Subject 5

Fig 3b. Q Analysis Program Output for final design mesh, Subject 6

	values assigned by subject 6				values assigned by subject 5				Descriptors
	R	T	C	S	R	T	C	S	
25.	2	*	1	2	2	*	1	1	Electronic analog simulation of behaviour of elementary reacting system
26.	2	2	1	1	1	2	1	1	Solution of differential equations using analog integration. Display variables as a function of time.
27.	1	2	0	1	1	1	*	0	Equilibrium constant as a function of temperature and Δ H.
28.	2	2	1	0	2	0	2	2	Approximate computation and display of heat in/out (thermostat on)
29.	1	0	0	1	1	2	1	1	Forward rate expression computation module (K_R as a function of temperature)
30.	1	0	0	1	1	2	1	1	Reverse rate expression computation module (K_F as a function of temperature)
31.	1	2	1	0	*	*	*	1	Equilibrium conditions in electronic feedback systems/oscillators
32.	1	2	0	1	2	2	2	2	Net rate (λ net) as voltage variable
33.	2	1	1	1	2	2	1	2	Integrator with arbitrary scaling
34.	2	1	1	2	1	1	2	2	Op. amp. comparator
35.									Scaling rate variables (division by stoichiometric) coefficients
36.	1	0	0	1	1	2	2	0	Arrhenius function computation (K_F)
37.	1	0	0	1	1	2	1	0	Arrhenius function computation (K_R)
38.	2	2	1	2	2	2	2	2	Computation of Δ H using subtractor
39.	2	2	2	2	2	1	1	2	Computation and display of reaction temperature (thermostat off) using comparator and integrator
40.	2	2	2	*	*	*	*	*	Temperature as voltage variable
41.	2	2	*	1	2	2	2	*	Analogy (isomorphism) between 29 and 30
42.	*	2	2	*	*	2	*	*	Analogy (isomorphism) between 36 and 37
43.	2	1	2	1	2	2	2	2	Division by a constant using potential divider
44.	1	2	1	1	1	2	1	1	Stoichiometric coefficients as user controls
45.	2	*	1	1	2	1	1	2	Analog integration
46.	2	*	1	2	2	*	2	1	Analog summation/subtraction
47.	1	*	0	0	1	*	0	0	Analog exponential function using antilog amplification
48.	1	*	0	0	1	*	0	0	Analog multiply/divide using transconductance multiplier
49.	2	2	1	1	2	2	1	1	A and E° as user controls
50.	2	2	2	2	2	2	2	1	Thermostat on/off control
51.	2	2	2	2	2	2	2	1	User temperature control

Descriptors
R = Reliability   C = Cost
T = Transparency   S = Environmental sensitivity

Values
* = irrelevant
0 = low reliability
1 =
2 = high reliability
* = irrelevant
0 = low transparency

* = irrelevant
0 = high cost
1 = low cost
2 = irrelevant
* = highly sensitive to environmental conditions
0 =
2 = low sensitivity

Fig 4: Assignment of Descriptor values for Final Design mesh. Subject 5.

NOTE: Descriptors only applicable to simulator operation and electronics portion of mesh.

Descriptors	values assigned by subject 6				values assigned by subject 5				Corresponding topics in final mesh for Subject 5
	R	T	C	S	R	T	C	S	
48. Complex reaction obtained by serial or parallel combination of simple reactions and their energetic exchanges in reaction vessel.	0	0	1	1	1	1	0	1	
49. Simple reaction	2	2	1	2	1	2	1	1	25
50. Energetic behaviours	1	2	*	0	*	1	*	*	
51. Rate and equilibrium constant (k) behaviours (computed value temperature)	1	2	0	1	1	2	1	1	
52. Cartesian product	*	1	*	*	*	2	*	*	
53. Energetic simulation	1	2	1	0	*	*	*	*	
54. Reaction simulation (energy is discounted)	2	2	2	2	*	*	*	*	
55. Temporal sequence	*	1	*	*	*	2	*	*	40
56. Computer temperature	0	2	0	1	0	1	1	0	
57. Behaviour at different k values and in equilibrium	0	0	0	0	1	1	*	1	
58. Temperature (T)	*	1	*	*	*	*	*	*	28
59. Constant temperature ΔH displayed	2	2	1	1	2	2	1	1	44
60. Manual switching of orders of reaction	2	2	2	2	1	1	1	1	56/57
61. Behaviour of k and rates at manually varied temperature	1	1	0	1	1	2	1	0	58
62. Behaviour of rates and of equilibrium constant at fixed $T = T^*$	0	2	1	0	1	2	1	2	
63. Δ H$_F$	1	0	1	0	1	1	2	1	38
64. Δ H$_R$	1	2	1	1	2	2	2	2	38
65. Manually variable temperature	1	2	0	2	2	2	2	1	51
66. Concentration of reactants.	1	2	1	1	1	2	1	2	
67. Simplification (formal condensation) of Mesh III (2) (Research Note 2) under 'forward reaction' (node 6, Mesh III (2)) (Research Note 2)	1	2	1	1	*	2	*	*	
68. Log A$_F$	1	0	1	1	1	1	1	1	49
69. Log A$_R$	1	0	0	0	1	2	1	1	49
70. E$_F$	0	1	0	1	*	2	*	*	49
71. E$_R$	0	1	0	1	*	2	*	*	49
72. Simplification (formal condensation) of Mesh III (2) (Research Note 2) under 'reverse reaction' (node 11, Mesh III (2)) (Research Note 2).	1	2	0	1	*	2	*	*	

Descriptors and descriptor values as in Fig 4

Fig 5: Assignment of Descriptor values for Final Design Mesh

Subject 6

Descriptors	R	T	C	S
Final mesh Subject 5	p < 0.001 *	p = 0.027 ✜	p = 0.13	p = 0.027 ✜
Final mesh Subject 6	p = 0.27	p = 0.014 ✜	p = 0.27	p = 0.50
Joint mesh	p = 0.073	p = 0.194	p = 0.387	p = 0.019 ✜

Fig 6 (a) Probabilities of obtaining the observed measure of agreement. between subjects for each descriptor. Values marked by * show a significant agreement at the 1% point ($p < 0.01$) . Values marked by ✜ show a significant agreement at the 5% point ($p < 0.05$)

Note: the probabilities were calculated by counting the frequency of matching value assignments. In this analysis, Values 2 and 1 have been merged and considered as a single positive evaluation. Analysis without this merging gives correspondingly lower frequencies of matching value statements.

Descriptors	R with T	R with C	R with S	T with C	T with S	C with S
Subject 5 Final mesh for Subject 5	p = 0.011 ✜	p < 0.001 *	p = 0.001 *	p = 0.062	p = 0.13	p = 0.004 *
Subject 6 Final mesh for Subject 5	p = 0.224	p = 0.13	p < 0.001 *	p = 0.062	p = 0.50	p = 0.13
Subject 5 Final mesh for Subject 6	p = 0.081	p < 0.001 *	p < 0.001 *	p = 0.081	p = 0.5	p < 0.001 *
Subject 6 Final mesh for Subject 6	p = 0.27	p = 0.036 ✜	p = 0.014 ✜	p = 0.42	p = 0.081	p = 0.5

Fig 6(b) Probabilities of obtaining the observed degree of association between descriptors. Values marked by * show a significant association at the 1% point ($p < 0.01$) . Values marked by ✜ show a significant agreement at the 5% point ($p < 0.05$)
Probabilities were calculated using the method described in the caption for Fig 6(a) .

APPENDIX 1

Specimen copy of the revised and
simplified design brief

INTRODUCTION.

You are to participate in a series of experiments being carried out in order to investigate individual differences in approach and methods in engineering design.

During the course of a number of design sessions you are expected to produce a circuit design and working prototype for an educational simulator.

Before commencing the design task, and its completion, you will be asked to take a number of psychological tests. During each design session you will be observed by an experimenter and at the end of each session there will be a period devoted to the analysis of the work done. The techniques to be used for the analysis will be explained in detail at the appropriate time.

As far as possible you should carry out the design task as you would in your normal working environment. You will be provided with a log book which is to be used for recording any work done outside design sessions.

The following materials and facilities are provided :

    (a) Design brief for an educational simulator to be used in an "A" level chemistry course.

    (b) Relevant chemistry texts to provide background information.

    (c) Component data sheets.

    (d) Texts on electronic theory and applications relevant to the design task.

    (e) Manual for minicomputer BASIC programming language.

    (f) Prototype hardware plus documentation , prototype simulator display, breadboard and control/monitoring panel. Analogue multiply/square/divide modules.

    (g) Power supply and test instruments.

You are free to engage in hardware construction and testing at any
stage in the design. A technician will be available to carry out
wiring tasks etc. Additional components required should be specified
and these will be obtained between sessions if they are not already
available in the laboratory.

If you feel that any of the materials or facilities provided are
inadequate or unduly restrictive, please say so. You are free to
enter into discussion with the experimenter at any time during the
sessions.

DESIGN BRIEF

Summary

You are required to produce a circuit design and working prototype
for an educational simulator to be used in an "A" level chemistry
course. The simulator is to be used to illustrate concepts in reaction
kinetics and equilibrium. Students should be able to use the simulator
to explore the behaviour of a reacting system under a wide range of
reaction conditions. The device should also allow the teacher to set
up specific problems to be solved by students. The user display and
control interfaces should be given careful consideration and you are
expected to incorporate, in the prototype, any user controls which you
consider necessary. (A prototype display panel is provided).

You may assume that the unit is to be manufactured using small scale
production facilities for a cost of approximately £200 per device.
You will be asked to produce an outline production specification for
the simulator and you should take into account, at the appropriate
stages in design, constraints relating to the following factors:
cost, size and weight (the unit is to be portable), ruggedness and
maintainability. Tradeoff between versatility of the simulator, its
reliability and cost are open to discussion.

OUTLINE OF SIMULATOR OPERATION

This section contains an outline description of the requirements for the simulator's operation. More detailed information is contained in the following section and in the chemistry textbooks provided.

As indicated by the prototype display panel, the reaction simulated has a maximum of 2 reactants, A and B, and 2 products, C and D. The reaction is represented by the stoichiometric equation:

$$N_A A + N_B B = N_C C + N_D D$$

Where N_A, N_B, N_C, N_D are the stoichiometric coefficients which may take values 0, 1, 2.

The reaction takes place inside an insulated reaction vessel. The temperature inside the reaction vessel may be maintained at a preset temperature by the action of a thermostat. (It is assumed that the simulated reactions involve no appreciable volume change).

Meters display the concentration of reactants and products, temperature, and the amount of heat removed from or supplied to the system by the thermostat.

Typically the student will be investigating the following features of the reaction :

(a) Reaction Profiles :- Plotting graphs of concentration versus time for reactants and/or products, measuring reaction rate.

(b) Reaction Order, Rate Expression, Rate Constant : Determining (or verifying) reaction order by using various graphical techniques, determining the rate expression and rate constant for a reaction.

(c) Rate of Reaction and Temperature : Investigating the way in which reaction rate varies with temperature. Determining values of 'activation energy' and 'frequency factor' from graphs and interpreting these quantities in terms of theoretical models for a reaction.

(d) Equilibrium Constants : Determining equilibrium constants for a reversible reaction, generally exploring the properties of the equilibrium state. Examining the relationship between equilibrium constant and temperature and the overall energy change for the reaction (enthalpy change).

The student is also to be encouraged to consider the overall relationships between macroscopic and microscopic properties of a reacting system and to suggest possible mechanisms and models for the simulated reactions.

The simulator is to have the following mode controls :

Reset : Initial concentrations, temperature etc may be set using the controls on the display panel.

Run : The simulated reaction takes place. The time scale is arbitrary but should allow the student sufficient time to take a series of meter readings for the purpose of plotting graphs. The time scale should also be chosen so that equilibrium conditions are established reasonably rapidly.

Hold : At any time during the course of a reaction the reaction may be halted and meter readings compared.

REP (Repetitive Operation) : The simulator cycles through Reset, Run, Modes, at a rate sufficient to allow the display of concentration versus time curves on an oscilloscope.

DETAILED SPECIFICATION
Stoichiometry and Rate of Reaction

As described in the previous section the general stoichiometric equation for the simulated reaction is :

$$N_A A + N_B B = N_C C + N_D D$$
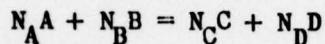
Where $N_A \ldots N_D$ may take values 0, 1, 2 with the restriction that the combinations of values N_A and $N_B = 2$ or N_C and $N_D = 2$ are not allowed.

The rate of reaction may be defined in such a way that it does not depend on the substance chosen to express the rate :

$$\text{Rate} = \frac{1}{N_C} \frac{d[C]}{dt} = \frac{1}{N_D} \frac{d[D]}{dt} = \frac{-1}{N_A} \frac{d[A]}{dt} = \frac{-1}{N_B} \frac{d[B]}{dt}$$

The bracketed terms represent concentrations of reactants or products. Concentration is the amount of substance per unit volume, the usual units being mol dm^{-1}.

Plots of concentration versus time for a reaction are known as reaction profiles. One method of determining reaction rate at a given instant is to measure the slope of a tangent to the reaction profile curve.

Effect of Concentration on Reaction Rate – Rate Equation
For most reactions the rate can be expressed as a function of concentration(s) of the form :

$$\lambda = K [A]^{V_A} [B]^{V_B}$$

For a reaction with stoichiometry :

$$N_A A + N_B B \rightarrow \text{products}$$

Where
λ = reaction rate (defined above)

$[A] [B]$ = concentrations of products

K = rate constant

V_A = "order of the reaction" with respect to A

V_B = "order of the reaction" with respect to B

V_A and V_B are normally integers with values 0, 1 or 2.

The sum $V_A + V_B$ is known as the (overall) "Reaction Order".

Empirical studies in reaction kinetics are frequently concerned with determining the rate equation for a reaction since this may provide information useful in the elucidation of a reaction mechanism for a complex reaction.

For the purposes of the simulator an important restriction is placed on the values of order coefficients :

For any simulated reaction $V_A = N_A$ and $V_B = N_B$ ie. the order of the reaction with respect of any reactant is equal to the stoichiometric coefficient for that reactant. In effect, this restriction means that all simulated reactions are 'elementary reactions', i.e. occur in a single step. In practice only a small number of reactions conform to this restriction.

The rate equation for a reaction may be written in differential form (using the definition of rate given above). In many cases the differential rate equation can be solved to give an integrated rate equation which gives an expression for concentration as a function of time. For example :
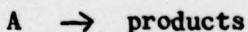
$$A \rightarrow \text{products}$$

$$-\frac{d[A]}{dt} = K[A] \qquad \text{Diff. Equation}$$

$$\text{In } [A]_0 - \text{In } [A] = Kt \qquad \text{Integrated Equation}$$

or

$$-\frac{d[A]}{dt} = K[A]^2 \qquad \text{Diff. Equation}$$

$$\frac{1}{[A]} - \frac{1}{[A]_0} = Kt \qquad \text{Integrated Equation}$$

$$A + B \rightarrow \text{products}$$

$$-\frac{d[A]}{dt} = K[A][B] \qquad \text{Diff. Equation}$$

$$\frac{1}{([A]_0 - [B]_0)} \left(\text{In } \frac{[B]_0}{[A]_0} - \text{In } \frac{[B]}{[A]} \right) = Kt \qquad \text{Int. Equation}$$

In many cases reaction order can be most easily verified by plotting a graph which should be linear according to the integrated rate equation.

Reversible Reactions

In the above discussion it has been assumed that the reaction proceeds in one direction only. In many cases this is unrealistic and the simulator is to be capable of demonstrating the dynamics of reactions in which both forward and reverse reactions occur.

For the general reaction :

$$N_A A + N_B B \rightleftharpoons N_C C + N_D D$$

Forward Rate Expression :

$$\lambda_F = K_F [A]^{N_A} [B]^{N_B}$$

λ_F = forward rate

K_F = forward rate constant

$\left.\begin{array}{c} N_A \\ N_B \end{array}\right\}$ = stoichiometric coefficients

Reverse Rate Expression :

$$\lambda_R = K_R [C]^{N_C} [D]^{N_D}$$

λ_R = reverse rate

K_R = reverse rate constant

$\left.\begin{array}{c} N_C \\ N_D \end{array}\right\}$ = stoichiometric coefficients

Net Rate :

$$\lambda_{net} = \lambda_F - \lambda_R$$

$$\lambda_{net} = \frac{-1}{N_A} \frac{d[A]}{dt} = \frac{-1}{N_B} \frac{d[B]}{dt} = \frac{1}{N_C} \frac{d[C]}{dt} = \frac{1}{N_D} \frac{d[D]}{dt}$$

## Equilibrium constant and ΔH (enthalpy change)

At equilibrium :-

Forward rate = reverse rate

$$K_F [A]^{N_A} [B]^{N_B} = K_R [C]^{N_C} [D]^{N_D}$$

$$\frac{K_F}{K_R} = \frac{[C]^{N_C} [D]^{N_D}}{[A]^{N_A} [B]^{N_B}}$$

This agrees with the "equilibrium law" which states that for a reaction with the stoichiometry :

$$N_A A + N_B B = N_C C + N_D D$$
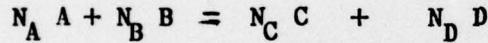
The equilibrium constant, $K_{eq} = \dfrac{[C]^{N_C} [D]^{N_D}}{[A]^{N_A} [B]^{N_B}}$

Variation of Rate Constant with Temperature

The rate constant for a reaction is normally related to temperature by an expression known as the Arrhenius Equation :

$$K = A e^{\frac{-E^*}{RT}}$$

Where

K	=	rate constant
A	=	'frequency factor'
E*	=	'activation energy'
R	=	gas constant
T	=	temperature ($^{\circ}$K)

The equation may also be written :

$$\ln K = \ln A - \frac{E^*}{RT}$$

The parameters A and E* may be related to 'collision' models for reacting molecules.

For a given reaction A and E* are assumed to be constant but the simulator must be capable of simulating reactions with a range of values for A and E*.

Variation of Equilibrium Constant With Temperature

The relationship between equilibrium constant and temperature is given by the expression :

$$\Delta G = RT \ln K_{eq}$$

where ΔG is the "Free Energy" for the reaction

R = gas constant

T = temp ($^\circ$K)

K_{eq} = equilibrium constant

ΔG can also be written as

$$\Delta G = \Delta H - T \Delta S$$

where H = enthalpy change for the reaction

S = entropy change for the reaction

T = temperature

For a reaction carried out a constant temperature (T) and at a constant pressure, the enthalpy change for the reaction is :

ΔH (at temp. T) = "The amount of heating or cooling done by a thermostat in order to compensate for either (a) heat absorption by an endothermic reaction (in bond formation) or (b) the heat emitted in an exothermic reaction (by bond breaking).

If the reaction is carried out under "standard conditions" (usually one atmosphere pressure with the reactants in the states normal for the temperature being used) the enthalpy change obtained is the "standard enthalpy" for the reaction. The standard enthalpy is usually denoted as $\Delta H^{\circ}(T^{\circ}K)$.

For an exothermic reaction ΔH is negative, for an endothermic reaction ΔH is positive.

The heat in/out meter on the display should indicate (at least qualitatively) the enthalpy change for the reaction.

Since the simulator is restricted to elementary reactions the relationship between Keq and temp may be derived as follows :-

$$K_{eq} = \frac{K_F}{K_R} = \frac{A_F \, e^{\frac{-E^*_F}{RT}}}{A_R e^{\frac{-E^*_R}{RT}}}$$

(Arrhenius functions for forward and reverse rate constants)

therefore :

$$Ln \, K_{eq} = Ln \frac{A_F}{A_R} - \frac{(E^*_F - E^*_R)}{RT}$$

But $E^*_F - E^*_R = \Delta H$ enthalpy change for the reaction

therefore :

$$Ln \, K_{eq} = \frac{A_F}{A_R} - \frac{\Delta H}{RT}$$

The relationship between activation energies for the forward and reverse reaction and ΔH is derived from a consideration of a "reaction co-ordinate" graph for a reaction and an interpretation of the activation energies as energy barriers to reaction.
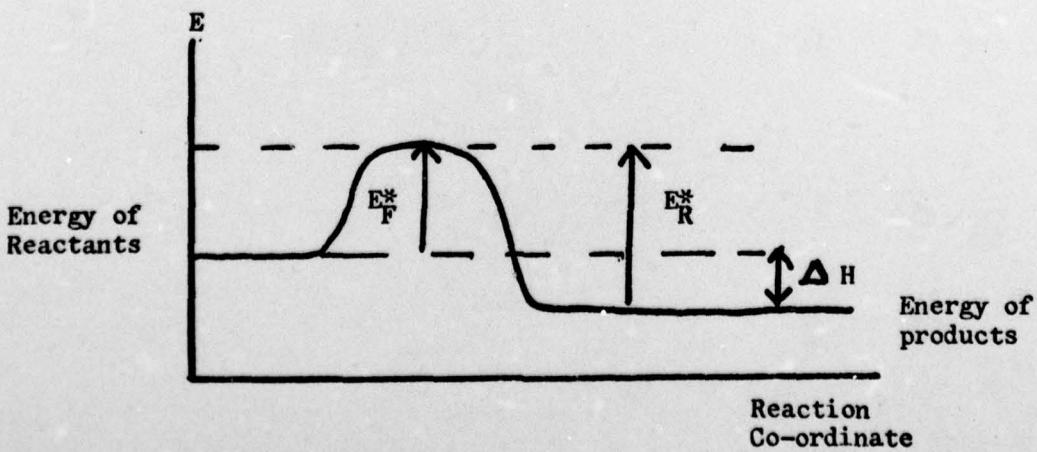
Interconnection of Simulations to Simulate Complex Reactions

At a later stage in the project we plan to extend the simulation
of reactions to include 'complex' reactions, ie. reactions occurring
as a combination of elementary reactions in parallel and/or series.
This is to be achieved by the interconnection of a number of the
type of simulator described in this specification. When simulations
are interconnected the resulting system should exhibit more complex
rate equations typical of many non-elementary chemical reactions.

The simulator design should, therefore, incorporate a means of
connecting with other simulators in a series/parallel arrangement.
It is intended that the simulated complex reaction should take place
in a reaction vessel with a single thermostatic temperature control,
ie. only one thermostat and display will be required. Impedance and
voltage level standards are open to discussion.

Programming

The production model of the simulator should be capable of being
programmed with values of stoichiometric coefficients, Arrhenius
parameters etc using a plug in card or similar device. This is
intended to allow the teacher to set up specific problems on the
simulator. The physical means for programming the simulator need
not be incorporated in the prototype but the designer should take
the programmability requirement into account where appropriate in
the circuit design. A specification for the means of programming the
simulator should be included in the production specification.

N

(d) Monitoring Sockets: Forward and reverse rate constants, $\triangle$ H.

(e) Mode Controls: RESET, RUN, HOLD, REP.

Any additional controls or monitoring sockets considered useful, either to the potential user or to facilitate simulator testing, should also be mounted on the prototype keyboard.

Performance Requirements

It is difficult to quantify the requirements for simulator accuracy needed to produce an effective tutorial device. Accordingly, the following performance guidelines are provided :

(a) Given input parameters set to produce an nth order reaction a graph of concentration of a reactant or product versus time should give the appropriate reaction profile. The order of the reaction as determined by the use of either the integrated rate equation or the initial rates method should be unmistakeably nth order.

(b) For any given setting of input parameters the value(s) obtained for the rate constant (from graphs) should be predictable and repeatable.

(c) The rate constant should approximately double for every 10° Kelvin rise in temperature and plots of Log. (rate constant) vs $(Temp)^{-1}$ should be linear.

(d) If the Activation Energy parameter, for either forward (E^*_F) or reverse reactions (E^*_R), is increased then the rate constant $(K_F$ or $K_R)$ should decrease.

(e) If the frequency factor A_F (for the forward reaction); A_R (for the reverse action); is increased then K_F or K_R should increase.

(f) If $E^*_F < E^*_R$ then the enthalpy change for the reaction ($\Delta H = E^*_F - E^*_R$) is negative and the reaction is exothermic.

If $E^*_F > E^*_R$ then the enthalpy change is positive and the reaction is endothermic.

(g) Observed values of the equilibrium constant for a reaction should agree with expected values (according to the "equilibrium law") to within typical margins of experimental error (10%).

(h) The equilibrium constant for a reaction should increase with temperature rise if the reaction is endothermic and decrease with temperature rise if the reaction is exothermic. Graphs of Log (equilibrium constant) vs. $(Temp)^{-1}$ should be linear.

APPENDIX 2

Copy Questionnaire administered to
all subjects before the experiment

Name :

Date of Birth :

Address :

Tel. No.   Home :   Work :

Education :

Secondary School :

"A" Level Subjects Passed :

Higher Education :

Degree(s) or Other Professional Qualifications :

<u>Employment/Electronics Design Experience</u> :

Please give a brief description of your present and previous jobs in terms of experience in the area of electronics design.

In which areas of electronics (if any) would you consider yourself to be an experienced designer (two years design work).

How would you describe your knowledge of chemistry? (Mention any courses of study in chemistry, eg. "O" level, degree, etc.)

Electronics Design :

A number of "design skills" are listed below. For each item could you indicate on the 1 to 5 rating scales :-

(A) In your opinion to what extent the skill is of importance in electronics design. (On the scale in column A).

(B) How do you rate your own competence in the skill?

	A					B				
	1	2	3	4	5	1	2	3	4	5
1. Mathematical analysis of system/circuit performance.	1	2	3	4	5	1	2	3	4	5
2. Systematic organisation and planning of phases of a design project.	1	2	3	4	5	1	2	3	4	5
3. Intuitive feeling for behaviour of electronic circuits/systems.	1	2	3	4	5	1	2	3	4	5
4. Analysis and understanding of performance requirements at a systems level.	1	2	3	4	5	1	2	3	4	5
5. Specification of subsystems or circuit modules.	1	2	3	4	5	1	2	3	4	5
6. Detailed design of circuitry.	1	2	3	4	5	1	2	3	4	5
7. Knowledge of (or reliable techniques for accessing) information concerning available components.	1	2	3	4	5	1	2	3	4	5
8. Systematic documentation during development phase of design.	1	2	3	4	5	1	2	3	4	5

		A.			B.		
	1 2 3 4 5			1 2 3 4 5			

9. Production of comprehensive final documentation 1 2 3 4 5 | 1 2 3 4 5

10. Ability to take into account and meet cost constraints. 1 2 3 4 5 | 1 2 3 4 5

11. Ability to take into account and meet reliability requirements. 1 2 3 4 5 | 1 2 3 4 5

12. Ability to take into account and meet constraints concerning ease of maintenance. 1 2 3 4 5 | 1 2 3 4 5

13. Awareness of current mechanical/electrical production techniques and constraints. 1 2 3 4 5 | 1 2 3 4 5

14. Fast and effective design debugging. 1 2 3 4 5 | 1 2 3 4 5

15. Ability to carry out systematic debugging of errors in circuit design. 1 2 3 4 5 | 1 2 3 4 5

16. Intuitive prediction/awareness of possible interaction between modules in a complex design. 1 2 3 4 5 | 1 2 3 4 5

17. Systematic analysis of interaction between modules. 1 2 3 4 5 | 1 2 3 4 5

18. Ability to design novel and effective circuitry. 1 2 3 4 5 | 1 2 3 4 5

19. Possession of a large repertoire of circuit design techniques. 1 2 3 4 5 | 1 2 3 4 5

20. Ability to produce and check out a detailed and accurate design on paper (before constructing prototype circuitry), in contrast to making up concrete models and check them out. 1 2 3 4 5 | 1 2 3 4 5

21. Ability to think globally (taking into account all aspects of design specification and system performance) at all stages in the design. 1 2 3 4 5 | 1 2 3 4 5

	A	B

22. Ability to think systematically (in a one-thing-at-a-time manner) through the various stages of the design.

    A: 1 2 3 4 5   B: 1 2 3 4 5

23. Utilisation of technological innovations (eg. new semiconductor devices).

    A: 1 2 3 4 5   B: 1 2 3 4 5

24. Ability to invent and compare many different designs, all of which satisfy at least some of the specifications (in contrast to concentrating upon one or a few designs).

    A: 1 2 3 4 5   B: 1 2 3 4 5

25. Ability to "see" the circuit operating in its region of application and to relate parts of the design to "real life" operations.

    A: 1 2 3 4 5   B: 1 2 3 4 5

26. Ability to imagine yourself in the position of a user (to appropriate consequences of defects of malfunctioning).

    A: 1 2 3 4 5   B: 1 2 3 4 5

List and rate any additional design skills which you consider important.

1.   A: 1 2 3 4 5   B: 1 2 3 4 5

2.   A: 1 2 3 4 5   B: 1 2 3 4 5

3.   A: 1 2 3 4 5   B: 1 2 3 4 5

4.   A: 1 2 3 4 5   B: 1 2 3 4 5

5.   A: 1 2 3 4 5   B: 1 2 3 4 5

References:

ATKIN, R. H. (1974) Mathematical Structures in Human Affairs London, Allen and Unwin.

BANNISTER, D., AND MAIR, J. (1968) The Evaluation of Personal Constructs, New York, Academic Press.

PASK, G. (1975) Conversation Cognition and Learning, Elsevier Amsterdam and New York.

PASK, G. (1976) Conversation Theory: Applications in Education and Epistemology, Elsevier, Amsterdam and New York.

THOMAS, L. F. (1971) "Interactive Method of Eliciting Kelly Grids", paper presented at the Occupational Section BPS Conference, Proceedings.